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9.2 Basic principles of the organization of the working process of combustion chambers

Theories of combustion and generalizations obtained from experiments allow us to make a series of conclusions which will determine the following basic principles of the construction of combustion chambers.

1. The division of combustion chambers into combustion zones and mixing zones.

The average temperature of gases in the turbine – $t_p = 750 - 900°$ – is sometimes (for example, in aviation) higher (up to 1200°) and is limited by the strength and durability of the components of its setting (basically, its blades—or "vanes"). In certain cases t_p does not go above 600-700° C. Naturally, no fuel can undergo complete combustion in combustion chambers under such conditions. Therefore, for the combustion of fuel it is necessary to isolate just part of the air going through the chamber, providing to a certain part of the combustion chamber the conditions for the formation of a highly reactive mixture and a significant process temperature. This part of the air—the primary air G_I—is directed to a combustion area of a specified size in the flue tube where fuel is then introduced. The remaining part of the air—the secondary air G_{II}—bypassing the combustion zone, is directed through special openings in the mixing zone of the flue tube (figure 9.1). Here this

air mixes with the combustion materials coming out of the combustion zone, which is provided for by a predetermined temperature of the gas in front of the turbine.

2. ***The gradual (stepped) feeding of primary air through the combustion zone***

This is necessary because in the beginning only a relatively small amount of air is required for the fuel spray (or "flame") (for the burning of small drops which quickly evaporate). Later, according to the level of preparation of the fuel, further portions of primary air are needed up to the theoretically necessary amounts, and practically even higher.

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An excess of air is needed to facilitate the conditions of carburetion (or "mixing") and the prevention of the chemical underburning of fuel, and also for the reduction of dissociations which arise at high temperatures of combustion. Usually, the optimal distribution of primary air through the combustion zone can be accurately determined only by making adjustments to the chamber experimentally on the stand (or "in the bed").

Figure 9.1—Diagram of the combustion chamber and the distribution of air:

1—frame; 2—flue tube; 3—nozzle (or "fuel injector")

In the diagram:

Топливо = Fuel

Зона горения = Combustion zone

Зона смешения = Mixing zone

Initially, in the design stage as a rule, there is a certain regularity in the distribution of air, often linear, as is shown in the diagram by the dotted line (see Fig. 9.1). In

this case, the quantity of G_I, and thereby $\alpha_I = \alpha_\Gamma = G_I/(G_T L_B)$, where G_T is the mass flow (or "expenditure") of fuel in kilograms/second, depends on the type of combustion chamber, the sort of fuel, and the organization of the working process.

It is necessary for the average temperature of gases in the combustion zone to be equal to 1600°-1800° C.

3. Flow turbulization in the combustion zone

This is necessary for the intensification of the processes of mass and heat exchange, the improvement of carburetion (or "mixing"), and an increase in the total speed of combustion as a result of the conversion of laminar combustion to turbulent combustion.

The flow becomes turbulent with the help of blade (or "vane") swirlers (registers), high-drag bodies, perforated plates, etc., which are set up in the front part of the chamber (as a frontal device), and also as a radial entry stream of air through openings in the walls of the flue tube.

4. Stabilization of the front of the flame in the combustion zone

The significant calorific intensity of the combustion chamber usually determines the average rate of flow which is significantly greater than the rate of the spread of the flame u_P.

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Therefore, in order to hold the fuel spray (or "flame") in a particular part of the combustion zone, special measures are necessary. In combustion chambers, swirlers (or "generators") or high-drag bodies of the frontal device serve as stabilizers. Behind these bodies there is established a zone of reverse current with lowered static pressure on the axis of the chamber, which is provided for by the ejection of gas in a ring-shaped stream flowing out of the register into a widening canal, and by its centrifugal effect it stabilizes the position of the fuel spray (or "flame") firing the entire fuel-air mixture.

Figure 9.2—Diagram of the flow of gas in the combustion zone:

1—nozzle (or "fuel injector"); 2—fuel cone; 3—opening (or "aperture"); 4—boundary (or "limit") of the zone of reverse current

In the diagram:

Воздух = Air

Зона обратных токов (ЗОТ) = Zone of reverse current

Зазор = Gap (or "clearance")

Ось камеры = Axis of the chamber

A diagram of the changes in axial velocities in various sections along the length of the flue tube in the combustion zone of the chamber are given in Fig. 9.2a. Radial and tangential velocities will depend on the construction of the frontal device and the parameters of the flow, in particular, with the use of blade (or "vane") registers—from the angle at which the blades are arranged relative to the axis of the chamber. This angle φ is usually taken as equal to 45-65° (fig. 9.2b), in line with the construction of the frontal device. With a further increase in the angle φ, the useful effect is usually not associated with additional drops in pressure.

5. ***The optimal distribution of (liquid) fuel spray across and along the flow of air to avoid particles of fuel landing on the walls of the flue tube***

It is recommended to give a full conic fuel spray (or "flame") in the area of the flow adjoining on the outside to the zone of reverse current, where the speed gradient will be maximized (fig. 9.3a). This is provided for by a good mixture of fuel with air, which is necessary for complete combustion.

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6. Organization of the cooling of the basic components of the combustion chamber

As a rule, the air coming into the chamber serves as the cooling agent. The parts of the chamber which are heated the most are the flue tube with its front part (the face), which is called the frontal device, and the nozzle (or "fuel injector"). The nozzle is cooled with air, the flow (fig. 9.3, #10) of which passes between the body of the nozzle (#2) and the barrel (or "sleeve", "socket") (#8) located in the center of the blade swirler (#9). This also prevents the coking (or "carbonization") of fuel as it goes out through the fuel injector nozzle (#7).

Figure 9.3—Change in the concentration of fuel according to the volume of the combustion zone:

1—flue tube; 2—nozzle (or "fuel injector"); 3—basic fuel cone; 4—fields of the local concentration of fuel in sections I-I, II-II, and III-III; 5—apertures for cooling air; 6—openings for primary air; 7—fuel injector nozzle; 8—barrel (or "sleeve", "socket"); 9—blade (or "vane") swirler; 10—primary air; 11—openings for cooling air

In the diagram:

Граница ЗОТ = Boundary (or "limit") of the zone of reverse current

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The frontal device and the flue tube (#1) are cooled by the secondary air which passes to the flue tube through a series of openings (#11) or ring apertures (#5) situated in several belts along the length of the flue tube. The ring apertures (as a continuous sheet) protect the walls more effectively than the openings, though the apertures let through a significant amount of air, increasing $\alpha_Г$. This air reduces the temperature of the combustion zone without oxidizing the fuel, since near the walls

there is almost no fuel. To eliminate this defect, the entrance to the ring aperture is covered with a wall having a row of small openings. These openings cause the air to pass through in small doses and also provide for the formation of a ring-shaped sheet of air which moves along the wall with less speed, but greater breadth.

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9.4 The working process of the combustion chamber

Diagram of the process

The working process of the combustion chamber of a gas turbine engine is very complex, and a conception of it can be more easily obtained by examining its separate elements and the influence of different factors. The aerodynamics of the flows of air and gas, the character of the feeding of fuel and its mixing with air, the ignition and stabilization of the flame, the conditions of mass and heat exchange, and the tendencies of thermal flux (or "heat generation", "heat segregation") along the length of the chamber—these are the basic elements of the working process.

The air coming into the combustion chamber, as a rule, has a significant velocity of 150 meters/second or greater—especially in a straight flow type of chamber where the entry of air comes directly from a compressor (or "pressure blower", "compression pump"). In this case a diffuser (fig. 9.8, #1) is placed before the frontal device of the flue tube. In the diffuser the velocity of the flow is lowered in stationary engines usually to 30-60 meters/second, and in aviation engines to 50-80 meters/second. Later, the primary air G_I is fed through the frontal device and a row of side openings in the flue tube (#6) to the combustion zone. The primary air makes up a part of the total flow of air passing through the combustion chamber, G_B. The quantity of primary air most often does not exceed 20-50% of G_B. This provides in the combustion zone the most favorable concentration of the mixture with a coefficient of surplus air $\alpha_\Gamma = G_I / (G_T L_O) = 1.1 / 2.0$.

A part of the primary air $G_{\phi p}$ enters through the frontal device directly into the beginning of the combustion zone. Usually the amount is $\alpha_{\phi p} = G_{\phi p} / (G_T L_O) = 0.2 / 0.5$ (see fig. 9.1). By swirling the air with the blade swirlers, the flow of air obtains significant radial and tangential velocities. The axial velocities of the flow usually do not exceed 12-17 meters/second, with the exception of combustion chambers of aviation gas turbine engines, where they sometimes reach 20-25 meters/second. The air coming out from the blade swirler moves in a spiral between the zone of reverse current and the flue tube. To avoid a break in the flow of air coming out of the swirler, the angle of the opening of the diffuser θ of the frontal device and the flow of air must be adjusted to each other. Usually a good streamline is obtained when the size of the angle φ at which the blades of the blade swirler are installed is $\varphi = \theta / 2$.

The temperature across the combustion zone (ЗГ) rises from T_B (the temperature of the air coming in) by the walls of the flue tube in a layer decreasing in thickness toward the end of the combustion zone, to T_P (the temperature of the combustion process) in the front of the flame by the border of the zone of reverse current. Inside the zone of reverse current, which is filled with combustion materials, the temperature is almost unchanged and has a significant magnitude (close to T_P).

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Figure 9.8—Diagram of the working process in the combustion zone:

a—diagram of the working process of the chamber; b—diagram of the burning up of fuel along the length of the combustion zone

In the diagram:

Продукты сгорания = Combustion materials; Горючая смесь = Gas mixture

ЗОТ = Zone of reverse current

The structure of the flow, the position of the front and the entire fuel spray (or "flame") in the combustion zone are shown schematically in fig. 9.8a.